Appendix A

Unsaturated Flow Computer Model SoilCover™ 2000

A.1 Unsaturated Flow Computer Model SoilCover™ 2000 Description

A.1.1 METHODOLOGY

One-dimensional hydrologic modeling of the water storage cover section for the ICDF was performed using SoilCover™ 2000, Version 5, developed by the University of Saskatchewan (Geo-Analysis 2000). SoilCover™ is a one-dimensional, finite-element package that models transient flow and energy conditions within a soil section. The model uses physically based methods for predicting the exchange of water and energy between the atmosphere and a soil surface and movement of water within a soil profile. The theory is based on the well-known principles of Darcy's and Fick's Laws, which describe the flow of liquid and vapor, and Fourier's Law, which describes conductive heat flow in the soil profile below the soil-atmosphere boundary. SoilCover™ predicts the evaporative flux from a saturated or an unsaturated soil surface on the basis of site-specific atmospheric conditions, vegetative cover, and soil properties and conditions. SoilCover™ requires extensive processing time due to its rigorous numerical methods to compute the water and energy balances in the soil profile.

SoilCover™ calculates the flow of water vapor and liquid water within the soil using equation (A-1) based on Fick's Law and Darcy's Law:

$$\frac{\delta h_w}{\delta t} = C_w^1 \frac{\delta}{\delta y}\left(k_w \frac{\delta h_w}{\delta y}\right) + C_w^2 \frac{\delta}{\delta y}\left(D_v \frac{\delta P_v}{\delta y}\right) \tag{A-1}$$

Where

h_w = Total head (m)

t = Time (s)

C_w^1 = Coefficient of consolidation with respect to the liquid water phase = $\frac{1}{\rho_w g}$.

Where

ρw = Mass density of water (kg/m3)

g = Acceleration due to gravity (m/s2)

y = Position (m)

k_w = Hydraulic conductivity (m/s)

C_w^2 = Coefficient of consolidation with respect to the water vapor phase = $\frac{P + P_v}{P \rho_w^2 g m_2^w}$.

Where

m_2^w = Slope of the moisture retention curve (1/kPa)

P = Total gas pressure in the air phase (kPa)

P_v = The partial pressure due to the water vapor (kPa)

D_v = Diffusion coefficient of water vapor through the soil (kg m/kN s) = $\alpha\beta\left(D_{vap}\frac{W_v}{RT}\right)$.

Where

α = Tortuosity factor of the soil = β2/3

β = Cross sectional area of soil available for vapor flow

Dvap = Molecular diffusivity of water vapor in air (m2/s) = $0.229\times10^{-4}\left(1+\frac{T}{273.15}\right)^{1.75}$

T = Temperature (°K)

Wv = Molecular weight of water (0.18 kg/kmole)

R = Universal gas constant (8.314 J/mole/°K).

Soil Temperature was evaluated on the basis of conductive and latent heat transfer using the equation (A-2) given below.

$$C_h\frac{\delta T}{\delta t}=\frac{\delta}{\delta y}\left(\lambda\frac{\delta T}{\delta y}\right)-L_v\left(\frac{P+P_v}{P}\right)\frac{\delta}{\delta y}\left(D_v\frac{\delta P_v}{\delta y}\right) \tag{A-2}$$

Where:

T = Temperature (ºC)

Ch = Volumetric specific heat of the soil as a function of water content (J/m3/ºC)

Dv = Diffusion coefficient of water vapor through the soil (kg*m/kn*s)

λ = Thermal conductivity of the soil (W/m/ºC)

Lv = Latent heat of vaporization of water (J/kg)

P = Total gas pressure in the air phase (kPa)

Pv = Partial pressure due to water vapor (kPa)

t = time (s)

y = position (m).

This equation takes into account soil freezing, which was verified by freezing tests using silica flour (Geo-Analysis 2000).

Based on input data points for moisture content and suction, SoilCover™ fits a continuous soil water characteristic curve (SWCC) using the equation developed by Fredlund and Xing (1994). The slope of the SWCC, m_2^w, is calculated from the derivative of this equation (A-3).

$$\theta_w = C(\psi)\frac{\theta_s}{\left\{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]\right\}^m} \qquad \text{(A-3)}$$

Where

θ_w = Water content at specified suction

$C(\psi)$ = Correction function

$$= 1-\frac{\ln\left(1+\psi/3000\right)}{\ln\left(1+1{,}000/3\right)}$$

θ_s = Saturated volumetric water content

ψ = Suction

a,n,m = Curve fitting parameters

e = 2.718281828.

The unsaturated conductivity function is determined from the equation (A-4) developed by Fredlund et al. (1994):

$$k_w = k_s\frac{\sum_{i=j}^{N}\frac{\theta\left(e^{y}\right)-\theta\left(\psi\right)}{e^{yi}}\theta'\left(e^{yi}\right)}{\sum_{i=l}^{N}\frac{\theta\left(e^{y}\right)-\theta_s}{e^{yi}}\theta'\left(e^{yi}\right)} \qquad \text{(A-4)}$$

Where

k_s = Saturated hydraulic conductivity

ψ = Suction.

The flow of water vapor at the soil-air interface, the evaporative flux, is calculated using a modified Penman equation (A-5):

$$E = \frac{\Gamma Q + \nu E_a}{\Gamma + A\nu} \qquad \text{(A-5)}$$

Where

E = Vertical evaporative flux (millimeters per day [mm/day])

Γ = Slope of the saturation vapor pressure versus temperature curve at the mean temperature of the air

Q = Net radiant energy available at the surface (mm/day)

ν = Psychometric constant

$E_a = f(u)P_a(B-A)$.

Where

$f(u)$ = Function dependent on wind speed, surface roughness, and eddy diffusion
$= 0.35(1 + 0.15Ua)$.

Where

Ua = Wind speed, kilometers per hour (km/hr)

Pa = Vapor pressure in the air above the evaporating surface

B = Inverse of the relative humidity of the air = 1/hA

A = Inverse of the relative humidity at the soil surface = 1/hr.

A.2 FINITE ELEMENT MESH

The conceptual cover section modeled for the ICDF site consisted of the following three layers:

- Cover Soil, 2.0 m of silt loam
- Capillary Break
    - 0.31 m of fine sand
    - 0.31 m of coarse sand
- Bio-Intrusion Layer, 0.93 m of cobbles.

The upper soil is the storage layer of the cover system and serves as the interface with the atmosphere and the underlying capillary break material. The capillary break consists of 0.31 m of fine sand and 0.31 m of coarse sand. The upper 0.93 m of the bio-intrusion layer was included in the model. Although the actual thickness of this layer will be 1.5 m, the 0.93-m thickness was sufficient to create the appropriate boundary condition (unit gradient) at the base of the capillary break. Defining the boundary condition at the base of the bio-intrusion layer as 1 kPa resulted in numeric convergence and minimized the water balance error (less than 0.1%) while resulting in a unit hydraulic gradient at the base of the coarse sand.

To accurately model the intense drying and rapid wetting from rain events, a node spacing as small as 0.2 cm was used at the surface of the cover soil. The position of all the nodes in the mesh is shown in Table 2-1. A user-defined monitoring node was identified at the contact between the base of the cover soil (silt loam) and the fine sand to monitor the flux through the upper cover section.

Initial conditions for each simulation were developed by running the model to a quasi-steady state over the simulation period and using the ending suctions as the initial conditions for the final runs. By using these simulations to generate the initial conditions for the final model, any biases or inaccuracies from the initial conditions assumed by the user were reduced.

Table 2-1. Finite element mesh.

Node	Soil	Elevation
1	silt	355.00
2	silt	354.80
3	silt	354.50
4	silt	354.00
5	silt	353.40
6	silt	352.40
7	silt	350.90
8	silt	348.60
9	silt	345.10
10	silt	340.00
11	silt	332.30
12	silt	323.30
13	silt	314.30
14	silt	305.30
15	silt	296.30
16	silt	287.30
17	silt	278.30
18	silt	269.30
19	silt	260.30
20	silt	251.30
21	silt	240.70
22	silt	231.70
23	silt	222.70
24	silt	213.70
25	silt	204.70
26	silt	195.70
27	silt	186.70
28	silt	177.70
29	silt	170.00
30	silt	164.90
31	silt	161.40
32	silt	159.20
33	silt	157.60
34	silt	156.60
35	silt	155.90
36	silt	155.50
37	silt	155.20

Table 2-1. (continued).

Node	Soil	Elevation
38 (Observation Node – Point D on Figure 2-1)	silt	155.00
39	fine sand	154.50
40	fine sand	153.70
41	fine sand	152.40
42	fine sand	150.40
43	fine sand	147.40
44	fine sand	144.40
45	fine sand	141.40
46	fine sand	138.40
47	fine sand	134.60
48	fine sand	131.60
49	fine sand	128.60
50	fine sand	126.60
51	fine sand	125.30
52	fine sand	124.50
53	fine sand	124.00
54	coarse sand	123.50
55	coarse sand	122.70
56	coarse sand	121.40
57	coarse sand	119.40
58	coarse sand	116.40
59	coarse sand	113.40
60	coarse sand	110.40
61	coarse sand	107.40
62	coarse sand	103.60
63	coarse sand	100.60
64	coarse sand	97.60
65	coarse sand	95.60
66	coarse sand	94.30
67	coarse sand	93.50
68	coarse sand	93.00
69	cobble	92.50
70	cobble	91.70
71	cobble	90.60
72	cobble	88.90
73	cobble	86.40

Table 2-1. (continued).

Node	Soil	Elevation
74	cobble	82.60
75	cobble	78.60
76	cobble	74.60
77	cobble	70.60
78	cobble	66.60
79	cobble	62.60
80	cobble	58.60
81	cobble	54.60
82	cobble	50.60
83	cobble	46.60
84	cobble	42.60
85	cobble	42.40
86	cobble	38.40
87	cobble	34.40
88	cobble	30.40
89	cobble	26.40
90	cobble	22.40
91	cobble	18.40
92	cobble	14.40
93	cobble	10.40
94	cobble	6.60
95	cobble	4.10
96	cobble	2.40
97	cobble	1.20
98	cobble	0.50
99	cobble	0.00